Electron-capture Rates of Nuclei at Stellar Environments and Nucleosynthesis

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1. GT strengths in pf-shell nuclei with GXPF1J and evaluation of e-capture rates at stellar environments

2. Nucleosynthesis of iron-group nuclei in type Ia supernova explosions (SNe)

3. Capture rates in pf-g shell nuclei (^{78}Ni) important for nucleosynthesis in core-collapse SNe

1. GT strengts in pf-shell and e-capture rates at stellar environmemts

GXPF1: Honma et al., PR C65 (2002); C69 (2004); A=47-66

KB3: Caurier et al., Rev. Mod. Phys. 77, 427 (2005)

KB3G A = 47-52 KB + monopole corrections

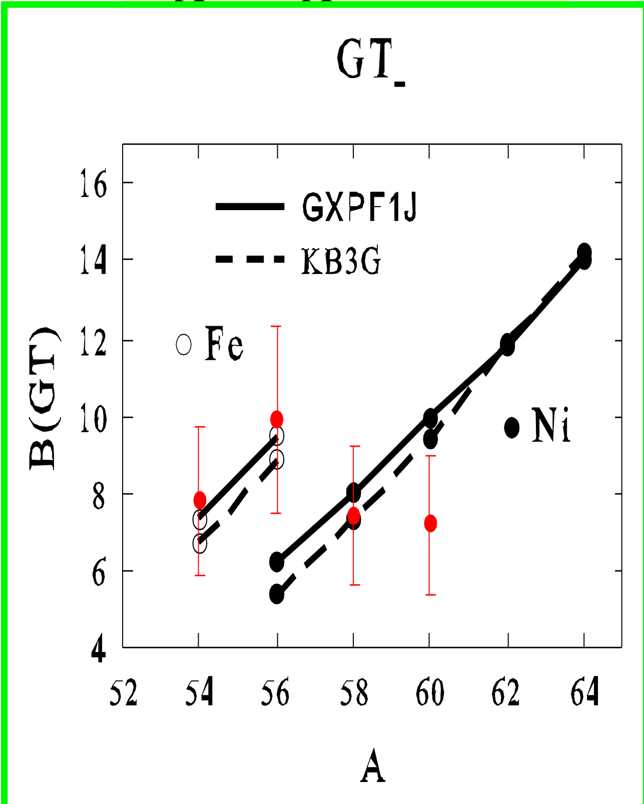
- **Spin properties of fp-shell nuclei are well described**

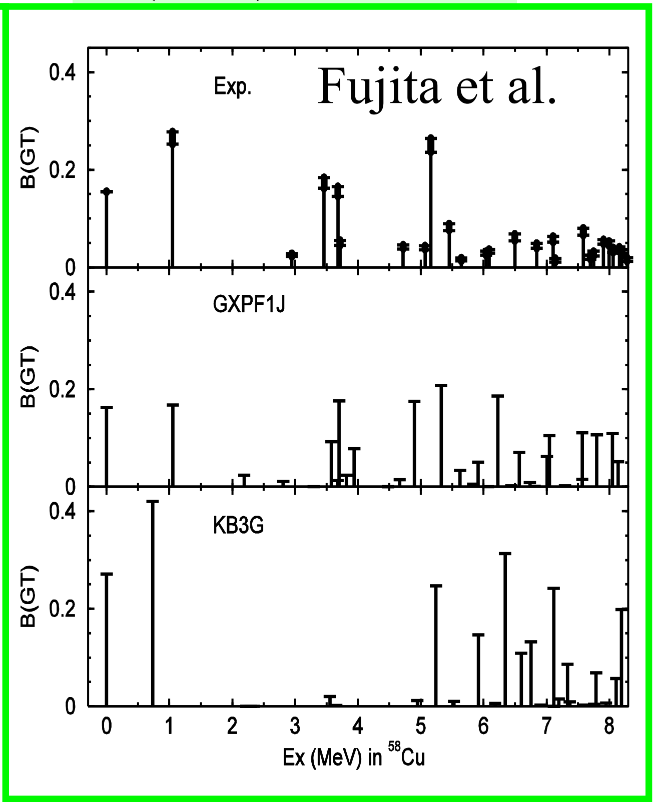
$g_A^{eff}/g_A^{free}=0.74$

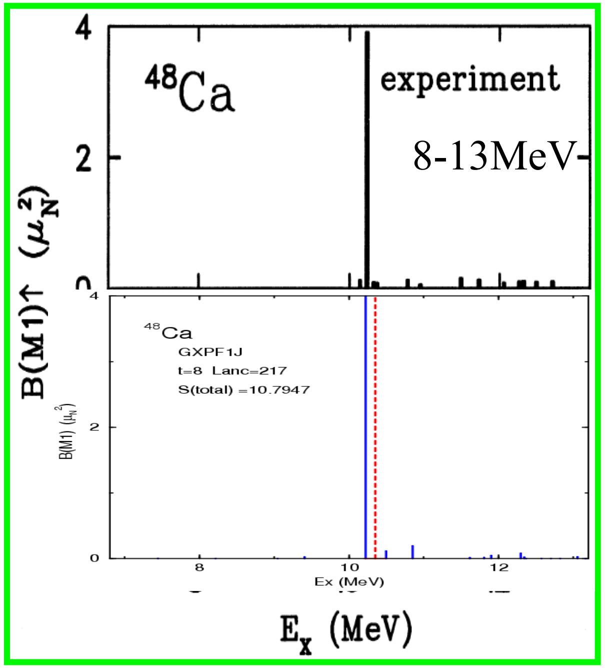
B(GT_) for ^{58}Ni

M1 strength (GXPF1J)

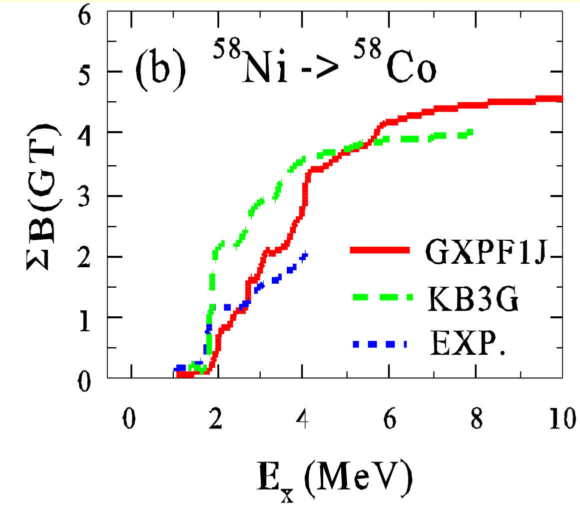
$g_S^{eff}/g_S=0.75\pm0.2$

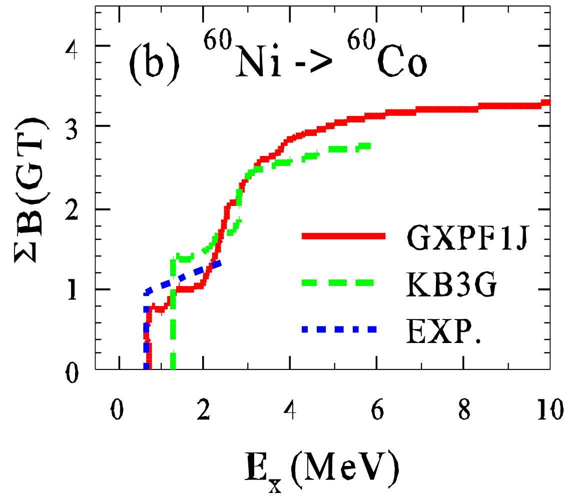


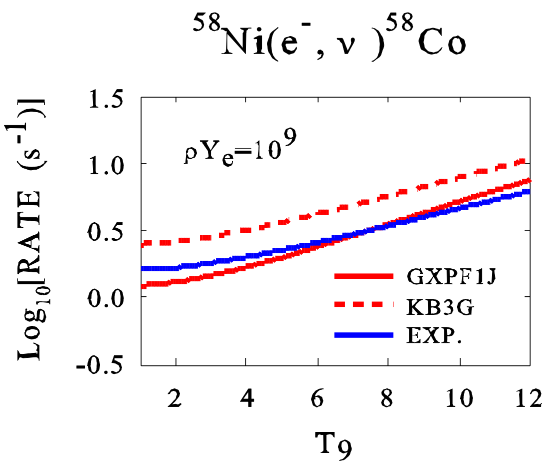


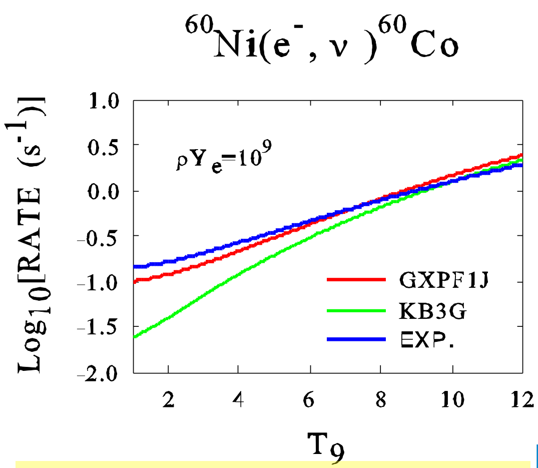


B(GT_+) and e-capture rates for ^{58}Ni and ^{60}Ni









Exp: Hagemann et al., PL B579 (2004)

Exp: Anantaraman et al., PR C78 (2008)

Suzuki, Honma, Mao, Otsuka, Kajino, PR C83, 044619 (2011)

Comparison of e-capture rates:
KB3G vs GXPF1A vs RPA

Cole et al., PR C86, 015809 (2012)

Electron-capture rates

$$\lambda = \frac{\ln 2}{6146(s)} \sum_i W_i \sum_f B(\mathrm{GT}; i \to f)$$

$$\times \int_{\omega_{\min}}^{\infty} \omega p (Q_{ij} + \omega)^2 F(Z, \omega) S_e(\omega) d\omega,$$

$$Q_{if} = (M_p c^2 - M_d c^2 + E_i - E_f)/m_e c^2,$$

$$W_i = (2J_i + 1) e^{-E_i/kT} / \sum_i (2J_i + 1) e^{-E_i/kT},$$

$$\rho Y_e = \frac{1}{\pi^2 N_A} \left(\frac{m_e c}{\hbar} \right)^3 \int_0^{\infty} (S_e - S_p) p^2 \, dp,$$

Y_e = No. electrons/No. b

$$S_e = \frac{1}{\exp(\frac{E_e - \mu_e}{kT}) + 1},$$

$$\mu_p = -\mu_e.$$

TABLE III. Electron chemical potential μ_e (in units of MeV) at high densities, $\rho Y_e = 10^7$–10^{10} g/cm^3, and high temperatures, $T = T_9 \times 10^9$ K.

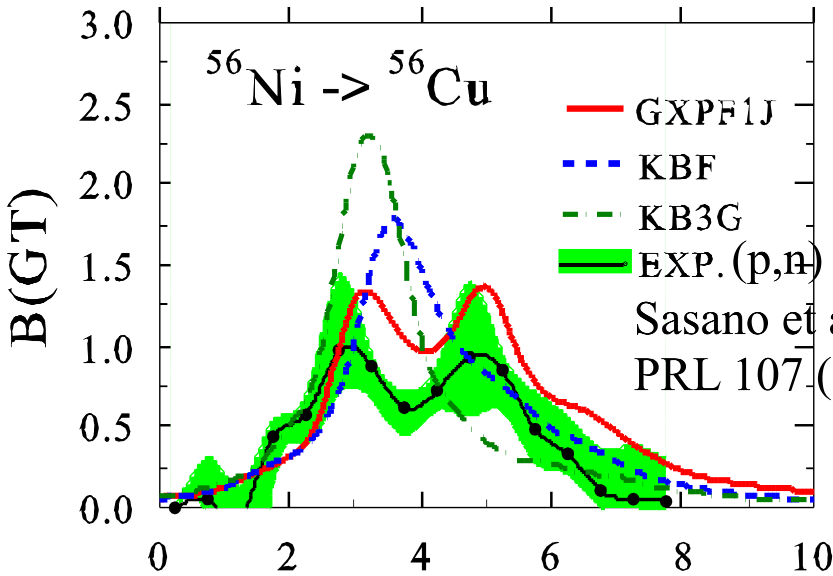
ρY_e (g/cm^3)	T_9									
	1	2	3	4	5	6	7	8	9	10
10^7	1.200	1.133	1.021	0.870	0.698	0.534	0.404	0.310	0.244	0.196
10^8	2.437	2.406	2.355	2.283	2.192	2.081	1.952	1.808	1.653	1.493
10^9	5.176	5.162	5.138	5.105	5.062	5.010	4.948	4.877	4.797	4.708
10^{10}	11.116	11.109	11.098	11.083	11.063	11.039	11.011	10.978	10.940	10.898

GT strength in ^{56}Ni: GXPF1J vs KB3G vs KBF

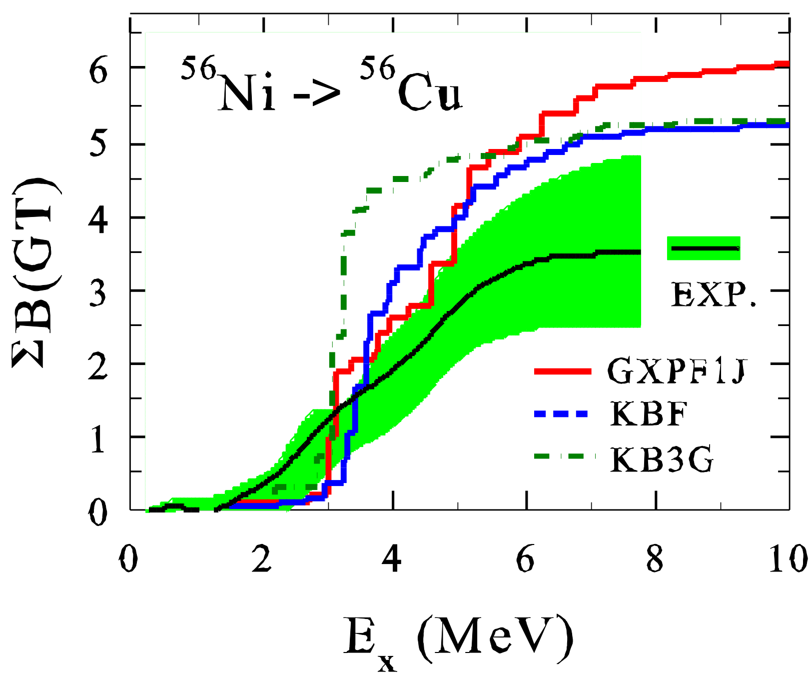
KBF: Table by Langanke and Martinez-

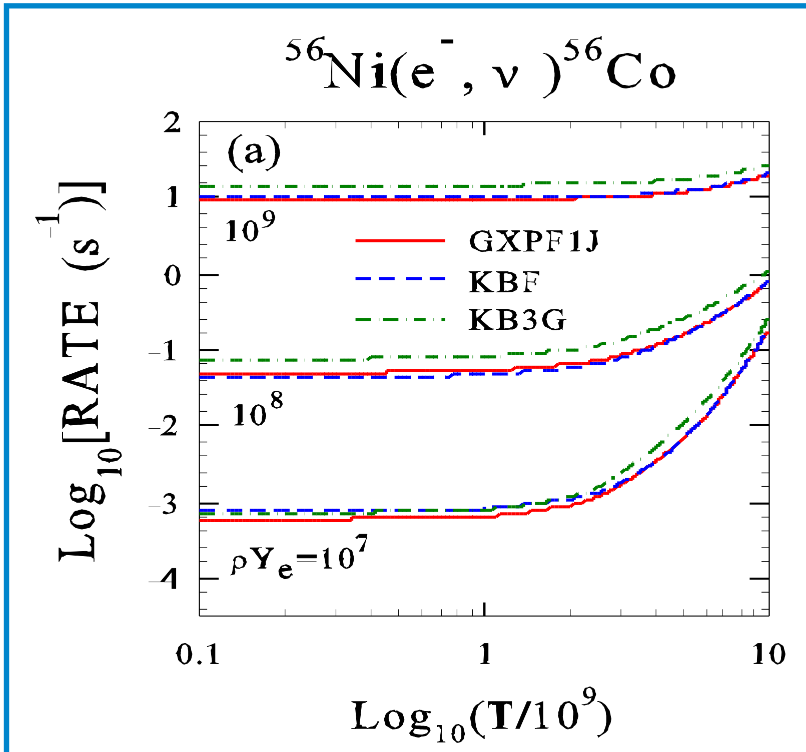
At. Data and Nucl. Data Tables 79, 1 (2001)

- fp-shell nuclei: KBF Caurier et al., NP A653, 439 (1999)
- Experimental data available are taken into account: Experimantal Q-values, energies and B(GT) values available
- Densities and temperatures at FFN (Fuller-Fowler-Newton) grids:



Sasano et al PRL 107 (2011)





2. Type-Ia SNe and synthesis of iron-group nuclei

Accretion of matter to white-dwarf from binary star

→ supernova explosion when white-dwarf mass ≈ Chandrasekhar limit

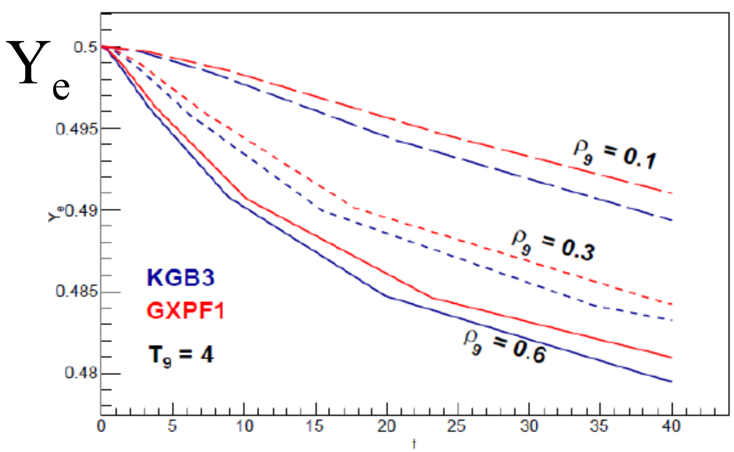
→ ^{56}Ni (N=Z)

→ ^{56}Ni (e$^-$, ν) ^{56}Co Y_e=0.5 → Y_e < 0.5 (neutron-rich)

→ production of neutron-rich isotopes; more ^{58}Ni

Decrease of e-capture rate on ^{56}Ni → less production of ^{58}Ni.

NSE(Nuclear Statistical Equilibrium) calculation



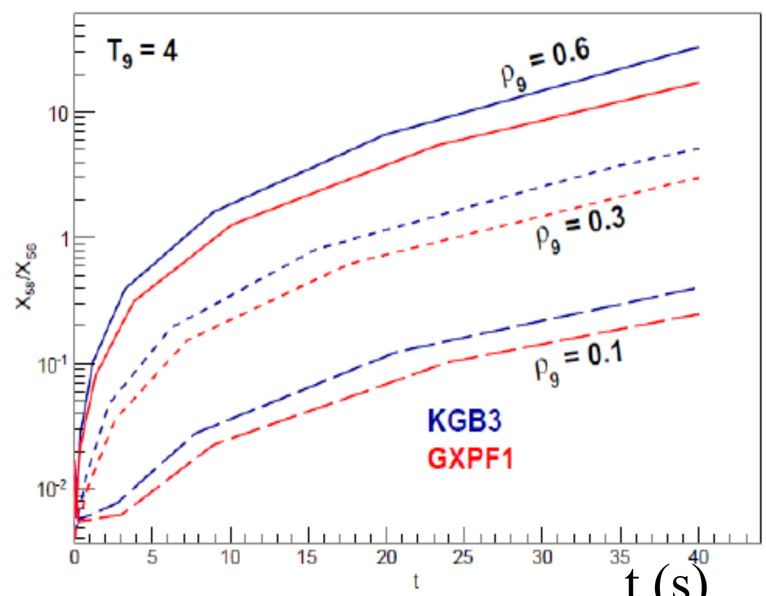
e-capture rates:

GXPF1J < KB3G

⟵⟶ Y_e (GXPF1J) > Y_e (KB3G)

Ratio between ^{58}Ni / ^{56}Ni

GXPF1 -> ^{58}Ni/^{56}Ni decreases



Famiano

Problem of over-production of neutron-excess isotopes such as ^{58}Ni, ^{54}Cr … compared with solar abundances

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 125:439–462, December

NUCLEOSYNTHESIS IN CHANDRASEKHAR MASS MODELS FOR TYPE Ia SUPERNOVAE AND CONSTRAINTS ON PROGENITOR SYSTEMS AND BURNING-FRONT PROPAGATION

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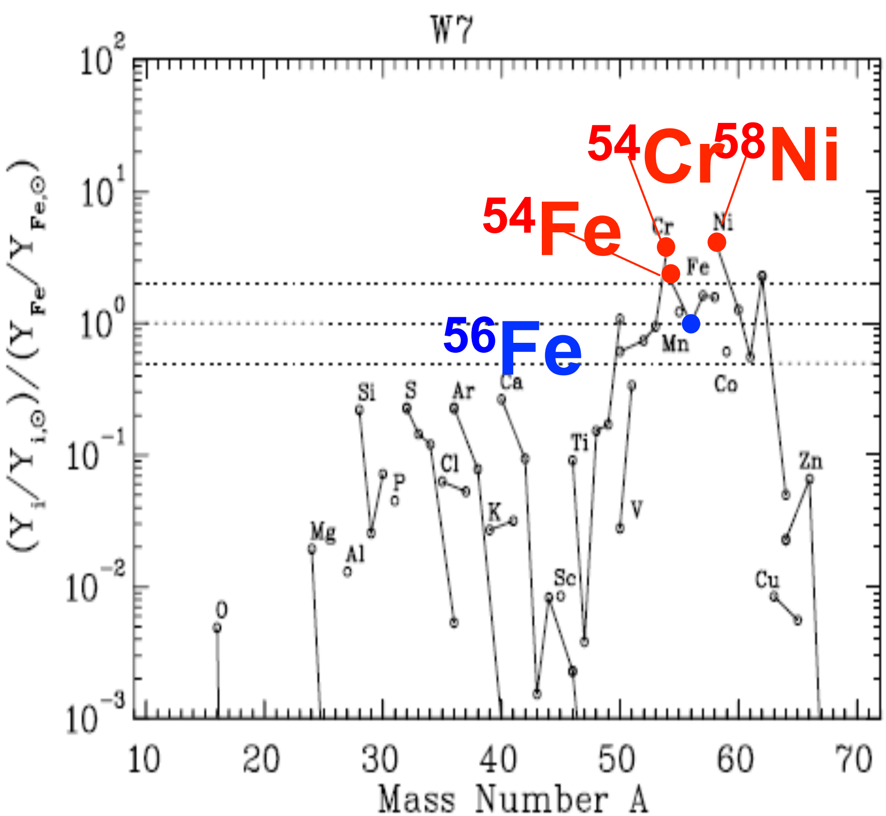
and ignition densities to put new constraints on the above key quantities. The abundance of the Fe group, in particular of neutron-rich species like ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{54,58}Fe, and ^{58}Ni, is highly sensitive to the electron captures taking place in the central layers. The yields obtained from such a slow central

Iwamoto et al.,
ApJ. Suppl, 125, 439 (1999)

e-capture rates with
FFN (Fuller-Fowler-Newton)



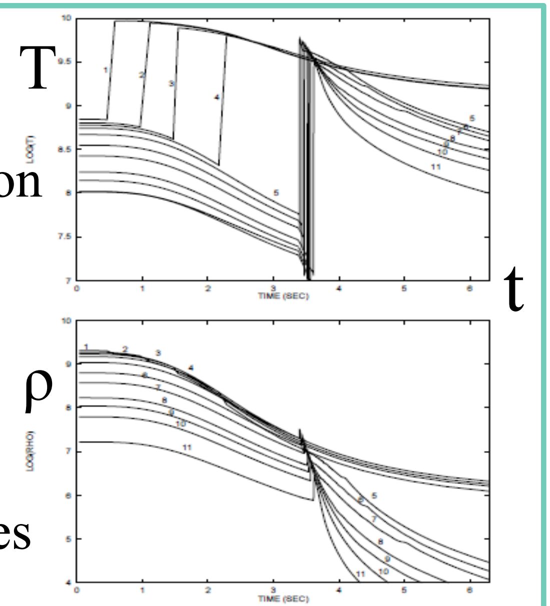
Type-Ia SNe W7 model: fast deflagration

Initial: C-O white dwarf, $M=1.0M_\odot$

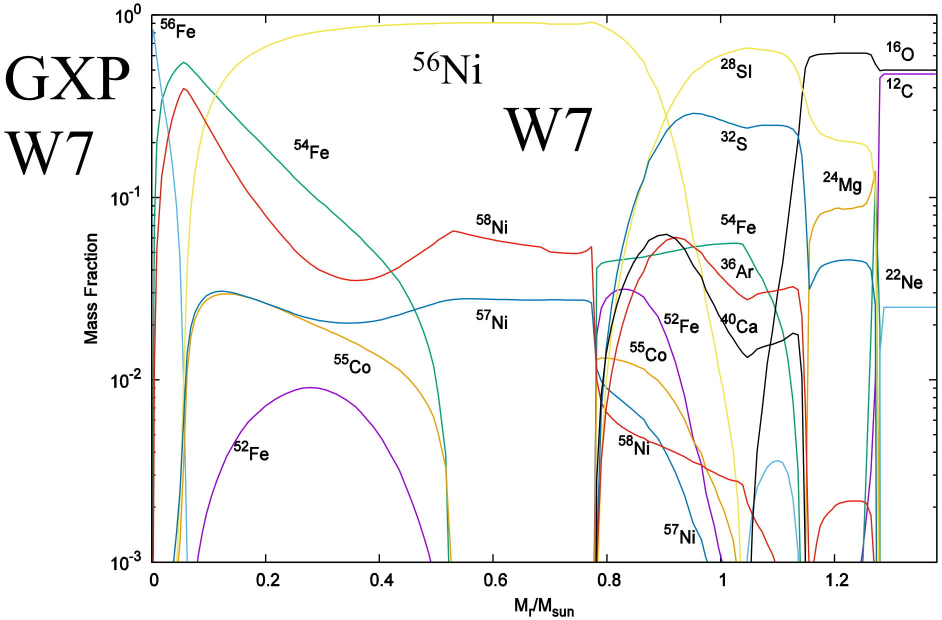
central; $\rho_9=2.12$, $T_c=1\times10^7$K

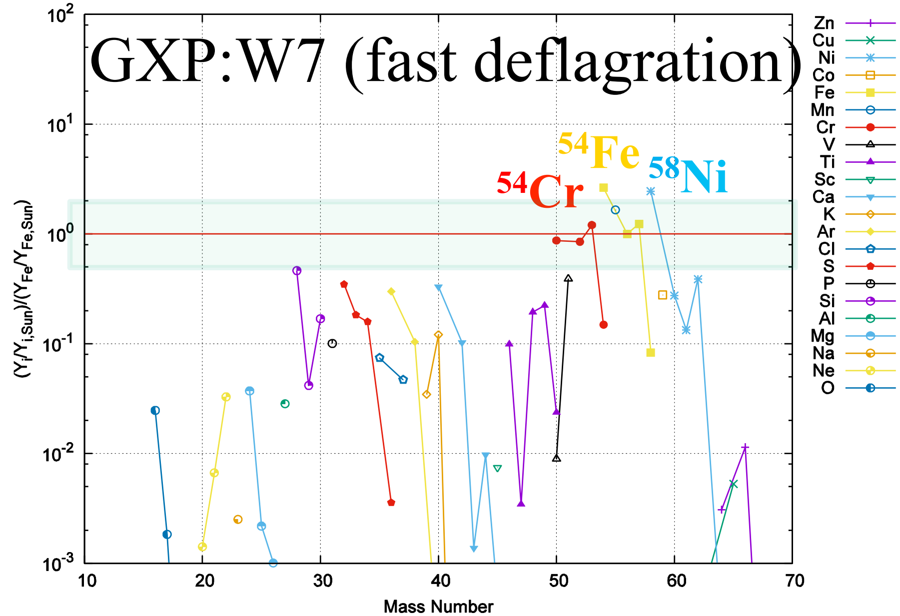
cf. WS15-DD1
Slow deflagration
+ delayed detonation

Right figure:
Time dependence
of density and
temperature for
different mass zones

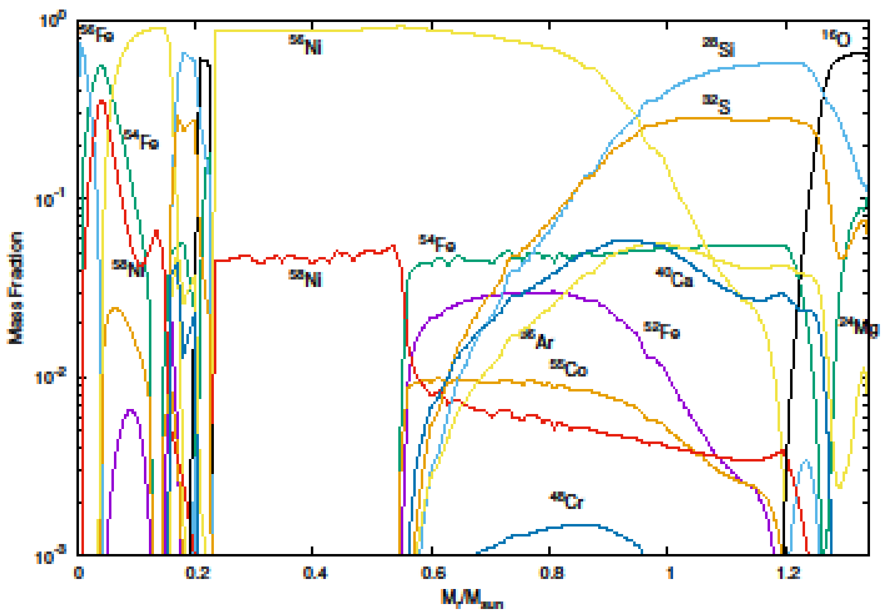


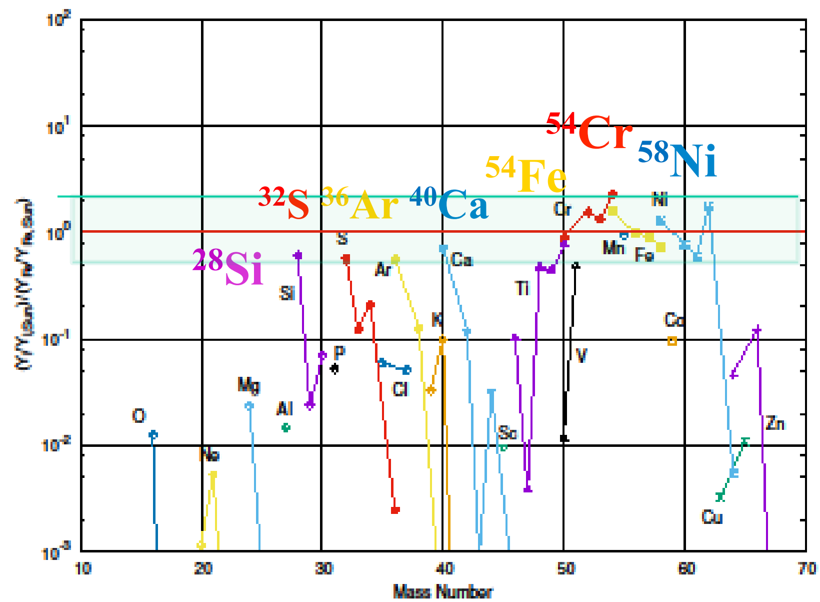
e-capture rates: GXP; GXPF1J (21≤Z≤32) and KBF (other Z)



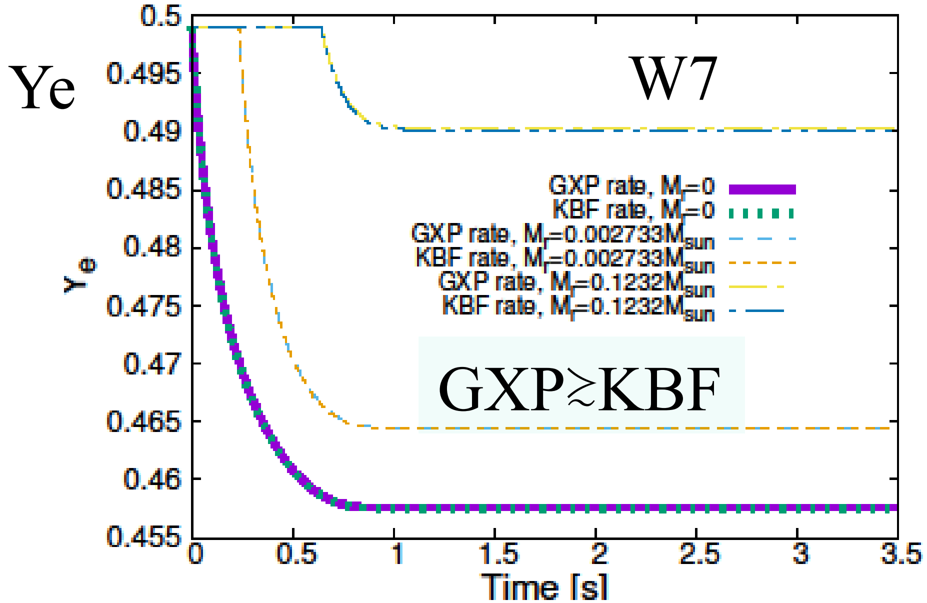


GXP: WDD2 (slow deflagration + detonation)

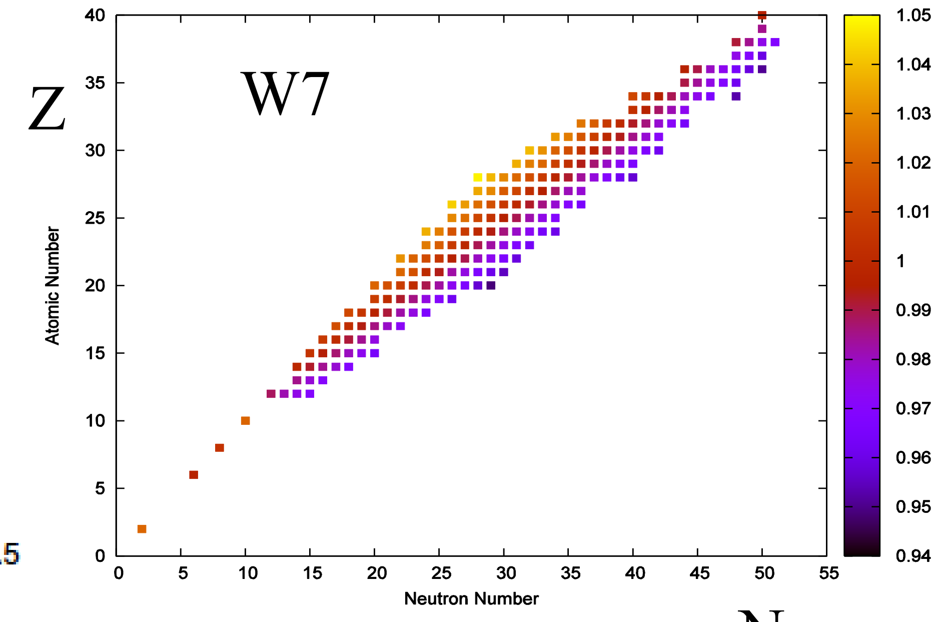


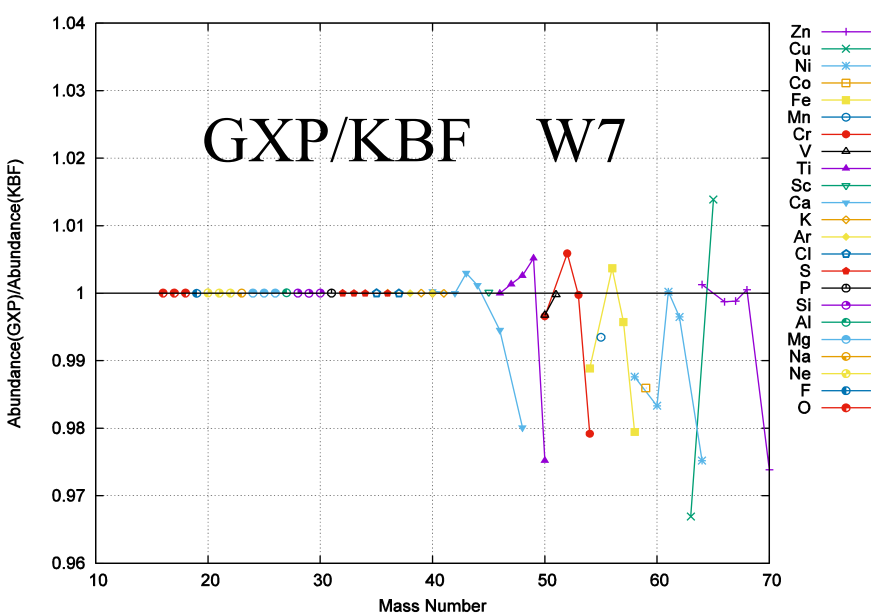


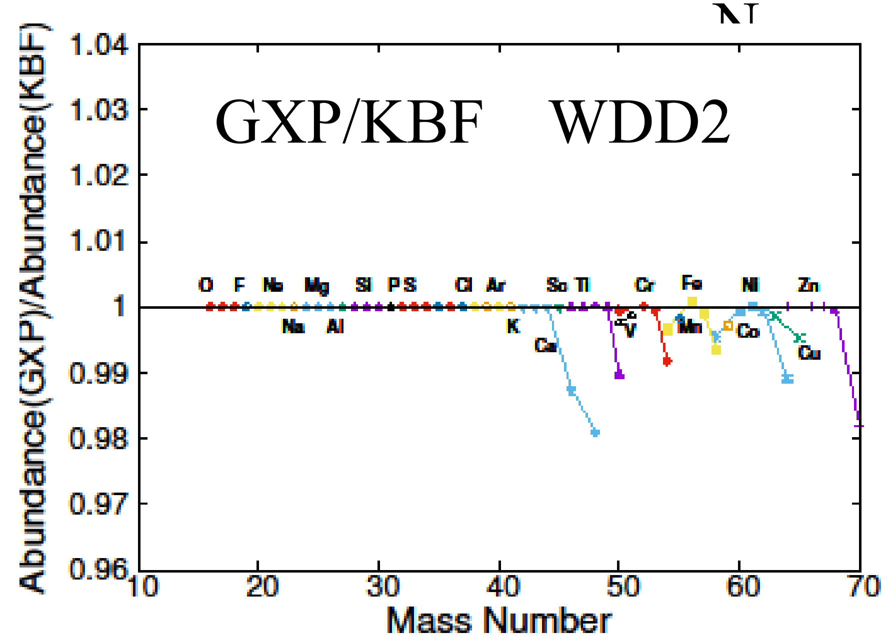
GXP vs KBF



GXP/KBF







cf. Langanke and Martinez-Pinedo, RMP 75, 819 (2003)

3. Weak rates of pf-g shell nuclei and core-collapse SNe

THE ASTROPHYSICAL JOURNAL, 816:44 (14pp), 2016 January 1

Approx.

$$\lambda_{EC} = \frac{\ln 2 \cdot B}{K}\left(\frac{T}{m_e c^2}\right)^5 \left[F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta)\right]$$

$$K = 6146\,\mathrm{s}, \quad B\,(=4.6) \text{ and } \Delta E\,(=2.5\,\mathrm{MeV})$$

$$\eta = \chi + \mu_e/T, \quad \chi = (Q - \Delta E)/T,$$

$$F_k(\eta) = \int_0^\infty \frac{x^k}{\exp(x-\eta)+1}\,dx,$$

$$F_k(\eta) = -\Gamma(k+1)\mathrm{Li}_{k+1}(-e^\eta),$$

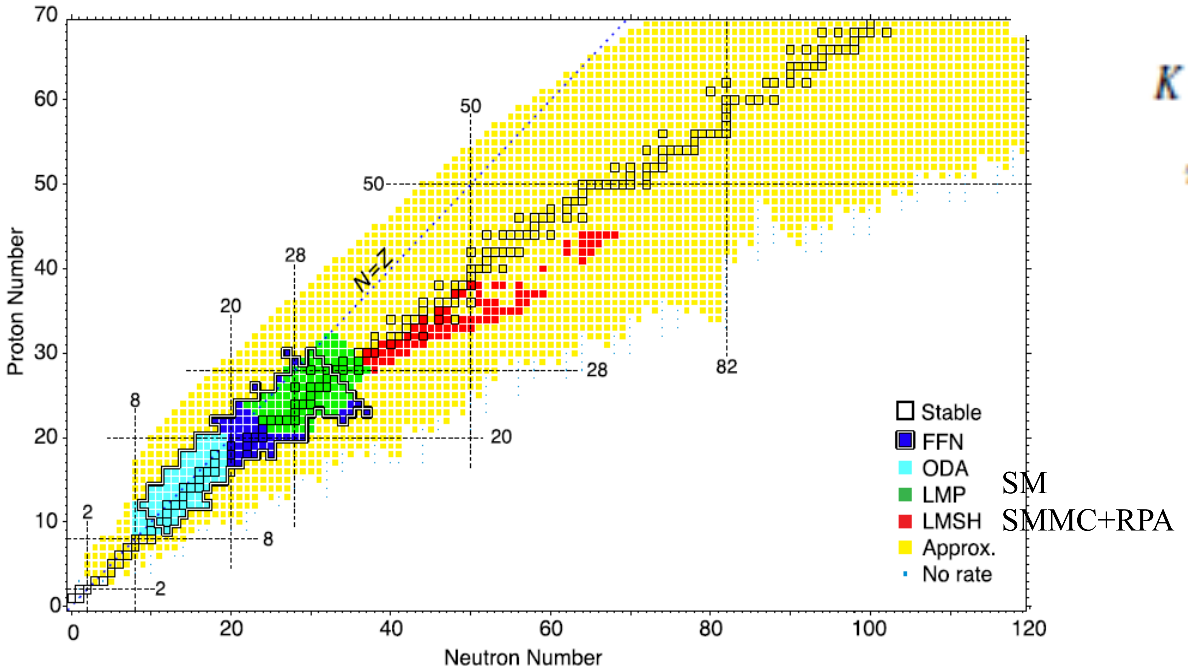


Figure 1. Chart of the nuclear species included in each weak rate table. The table to which a species belongs is given by the color and legend in the figure. The Oda set contains rates for lower-mass *sd*-shell nuclei (light blue), the LMP set contains rates for the intermediate-mass *pf*-shell nuclei (green), and the LMSH set contains rates for the heavier mass *pfg/sdg*-shell nuclei near stability (red). The FFN tabulation provides rates across the *sd*- and *pf*-shells (dark blue). Squares individually bordered in black are stable nuclei. The tables are mutually exclusive except for FFN, which spans many nuclear shells. To distinguish between nuclei with rates from FFN and another table, the border of the FFN set has been outlined with a black and white line.

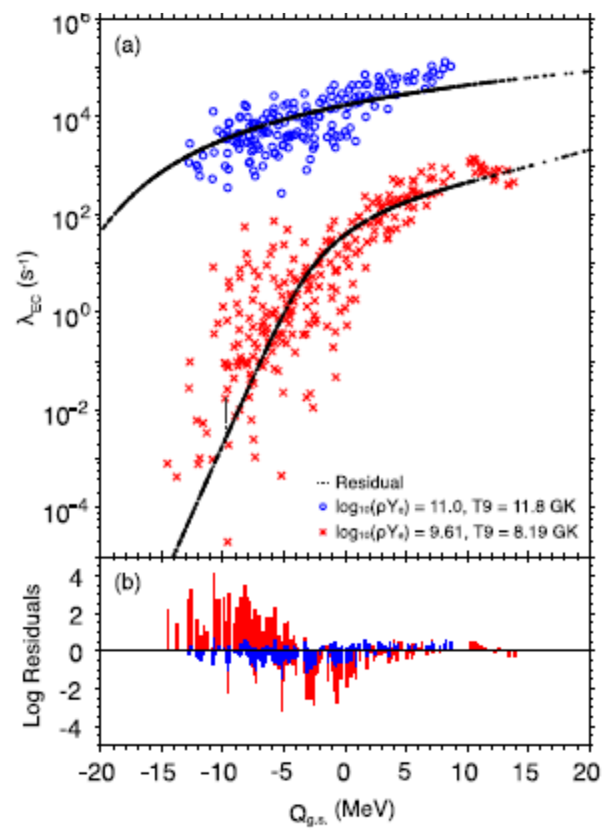
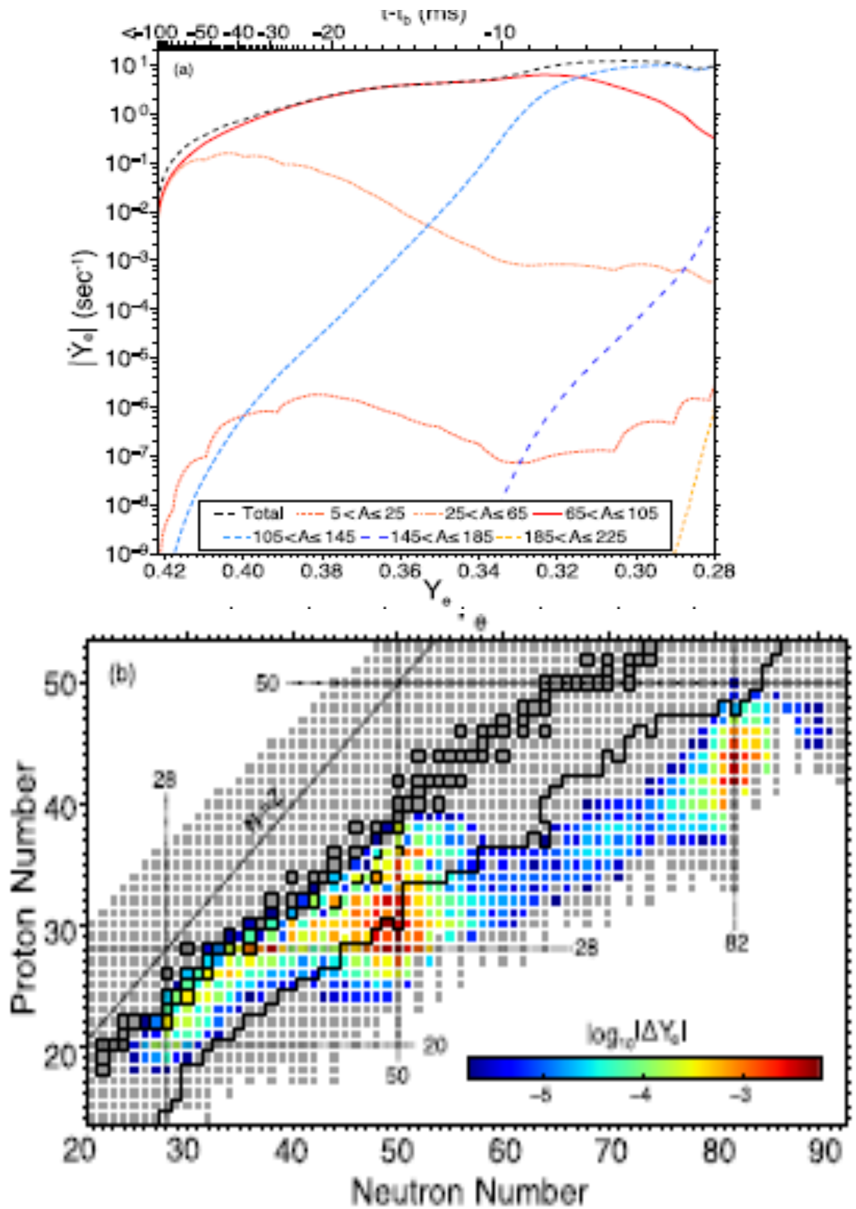


Table 1
Density, Temperature, and Mass Ranges for the Compiled Weak Rate Set

Table	Model Space					T (GK)	$\mathrm{Log}_{10}(\rho Y_e\ \mathrm{g\ cm}^{-3})$	Reference
	s	p	sd	pf	pfg/sdg			
FFN	x	...	x	x	...	0.01–100	1.0–11	Fuller et al. (1982)
ODA	x	...	x	...	...	0.01–30	1.0–11	Oda et al. (1994)
LMP	x	...	...	x	...	0.01–100	1.0–11	Langanke et al. (2003), Langanke (2001a)
LMSH	...	...	...	...	x	8.12–39.1	9.22–12.4	Hix et al. (2003), Langanke et al. (2001a)
Approx.	x	x	x	x	x	...	...	Langanke et al. (2003)

Sullivan et al., ApJ. 816, 44 (2016)

Which nuclei affect $\dot{Y}_e$ (change of Y_e) most in core-collapse process?

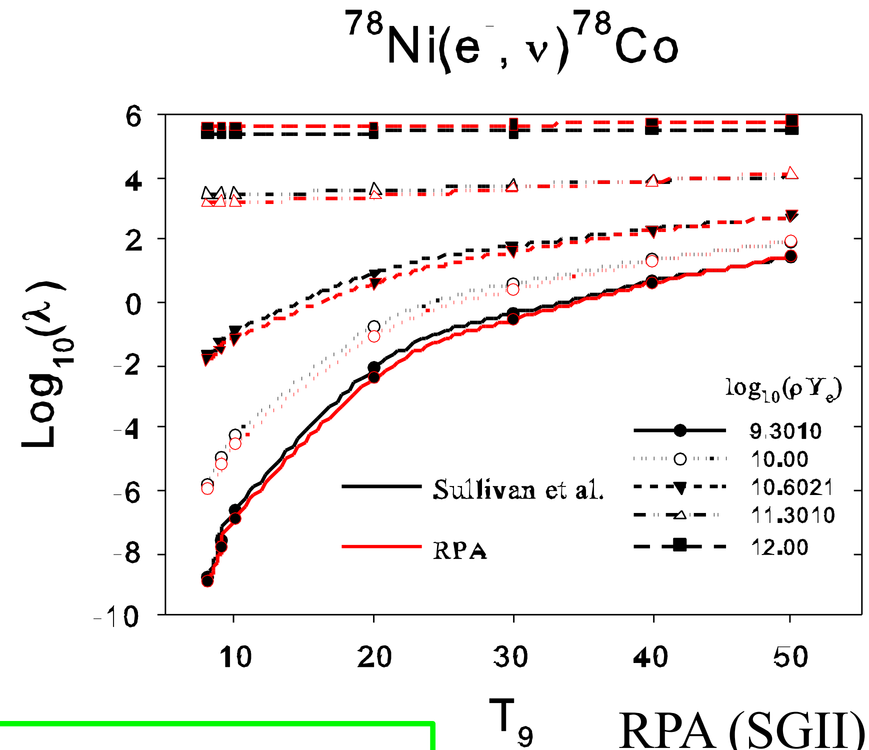


^{78}Ni

- Approx. rates of Sullivan et al.
- RPA
- SM (pf-$g_{9/2}d_{5/2}$; modified A3DA)

Q= -18.88 MeV (set to be HFB21's)

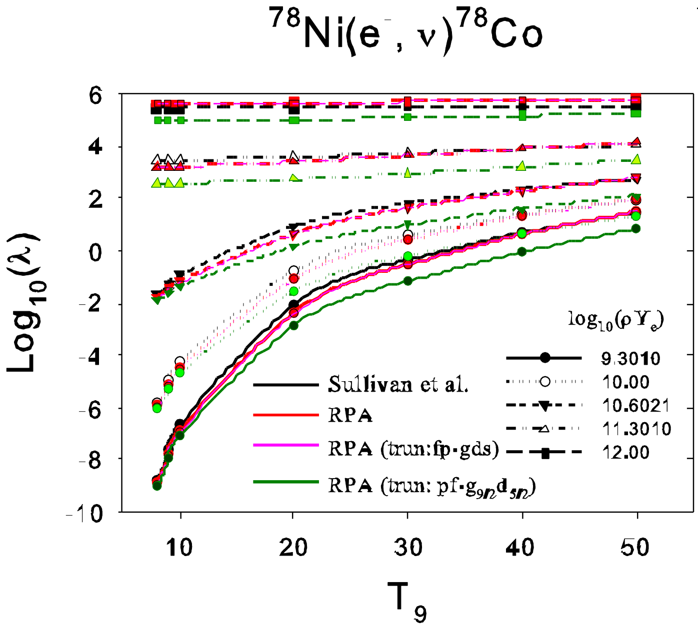
g_A^{eff}/g_A=0.74 (1.0) for GT (other multipoles)

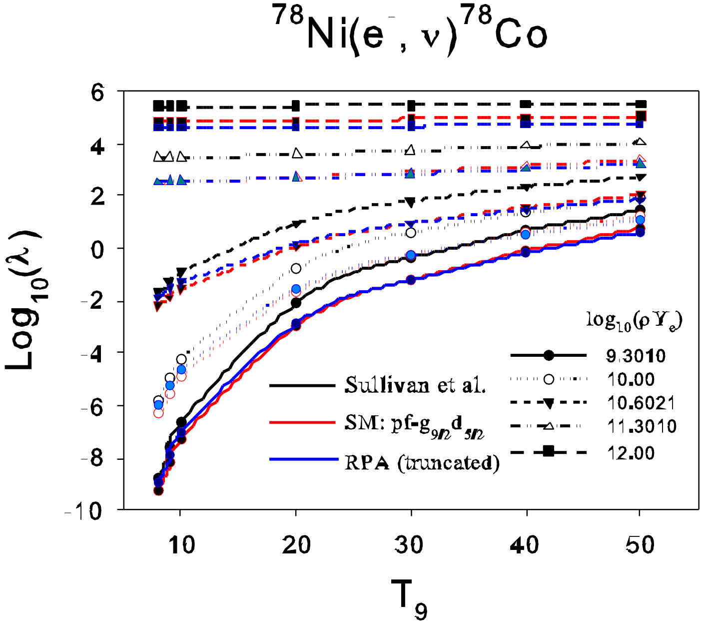


RPA (SGII)

RPA ≈ Sullivan

Effects of truncation of space

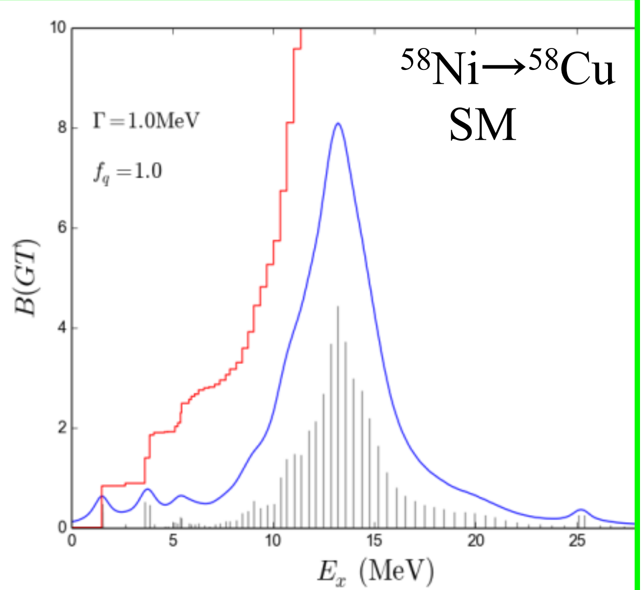


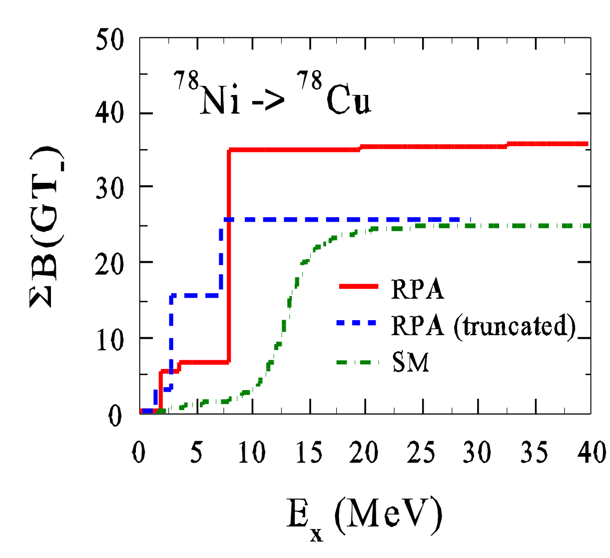


pf-gds is enough, pf-$g_{9/2}d_{5/2}$ is not enough RPA(pf-$g_{9/2}d_{5/2}$)≈SM(pf-$g_{9/2}d_{5/2}$)

SM: modified A3DA;
pf-$g_{9/2}d_{5/2}$
Y.Tsunoda et al.,
PRC 89, 031301R (2014)
$E_x(2^+)$ = 2.8 MeV
Up to 5p-5h outside filling config. of ^{78}Ni

SM with pf-gds in progress





Sum of the strengths

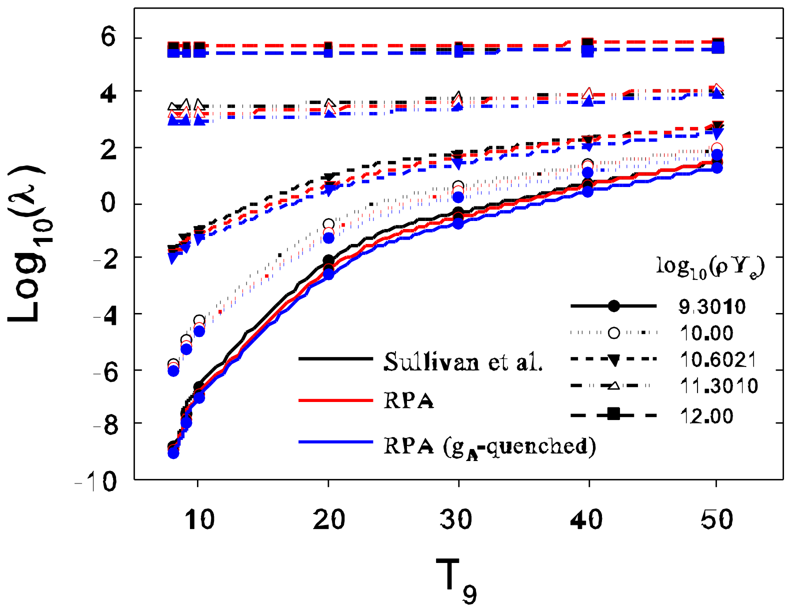
$$S=\Sigma_i\langle g.s.\,|O^+\,|i\rangle\langle i|O|g.s.\rangle$$

	SM(pfg9d5)	SM(pfgds)	RPA (full)
GT	0.0078	0.0804	0.3711
E1	3.202	4.368	4.231
SD0	0.046	12.083	12.378
SD1	1.603	20.241	20.683
SD2	2.616	14.098	15.995

SM: |g.s.> = |pfg9d5>

Effects of g_A^{eff}

$^{78}Ni(e^-, \nu)^{78}Co$



$g_A^{eff}/g_A = 0.74$ in all multipoles
vs. $g_A^{eff}/g_A = 0.74$ in GT only

- Q-values (calculated values)
  - FRDM: -21.19 MeV
  - RPA(HFB21): -18.88
  - RPA (SGII): -16.29
  - SM (A3DA: 5p-5h): -18.1
  - (-27.426 MeV without Coulomb correction; $\Delta E_C=7.86+1.5\approx 9.36$)

Summary

•A new shell model Hamiltonian GXPF1J well describes the spin responses in pf-shell nuclei .

GT strengths in Ni and Fe isotopes, which are generally more spread compared to KB3G and KBF, are consistent with recent experimental data, especially in ^{56}Ni.

・ Electron capture rates in Ni isotopes (^{56}Ni etc.), iron-group nuclei and pf-shell nuclei are evaluated with GXPF1J at stellar environments, and applied to nucleosynthesis in Type Ia SNe.

・ GXPF1J gives smaller e-capture rates compared with KB3G, KBF and FFN, and leads to larger Y_e with less neutron-rich isotopes, and thus can solve the over-production problem in iron-group nuclei.

・ e-capture rates for ^{78}Ni are evaluated by RPA and SM (pf-$g_{9/2}d_{5/2}$)

RPA ≈ Sullivan's formula (g_A^{eff}/g_A for SD transitions =1.0)

SM: extension to fp-gds configurations is in progress

Precise evaluation of Q value is important.

Collaborators

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